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Models in Cost-Effectiveness Analysis: An Example

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PREFACE

This paper was presented at the 21st Annual National Forum of The American Helicopter Society on 13 May 1965. It describes some approaches to modeling for systems analysis or cost-effectiveness studies.

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INTRODUCTION

Elements of Cost-Effectiveness Analysis

Cost-effectiveness studies are an aid to resource allocation decisions. The principal elements of a cost-effectiveness analysis are:

Objective(s) (functions to be accomplished)

Alternatives (feasible ways of achieving the desired military capability or accomplishing the function)

Costs of resource requirements for each alternative

Models (sets of mathematical or logical relationships among the objectives, alternatives, environment and resources)

Criterion for choosing the preferred alternative

The criterion specifies the relation between the measure of effectiveness and the measure of cost that will result in preference. The effectiveness measure should express the extent to which the objective is being accomplished. The measure of cost must be consistent with the overall framework of the resource allocation problem, e.g., net future total peacetime cost of ownership for N years.

An extensive discussion of the criterion of preference is beyond the scope of this paper; Chapter 9 of Hitch and McKean, The Economics of Defense in the Nuclear Age, [1/] covers the criterion problem admirably. However, some problems in selection of criteria, and in selection of a preferred alternative within the constraints of a given criterion, are examined in the final section of the paper, "Cost-Effectiveness Model."

Regardless of the specific criterion to be applied, the effectiveness and cost of each of the alternatives must be estimated and related. These estimates are made by means of several types of logically interrelated models. The emphasis of this paper is on the conceptual design and function of the principal types of models used in cost-effectiveness analysis.

Role of Models

All models used in cost-effectiveness analysis are formalized relations among abstractions from the real world. They perform a dual purpose of (a) reducing the problem to manageable proportions, and (b) identifying those variables and parameters that are significant to the decision process.

The problem in any cost-effectiveness analysis is how to get from "here to there"; from the estimate of effectiveness to the estimate of cost of each alternative; and from the effectiveness and costs of each alternative to selection of the preferred alternative for accomplishing the objective. This progression cannot be accomplished directly, but is made possible by four principal types of interrelated models:

- Effectiveness models
- System and organization models
- Cost models
- Cost-effectiveness models

The interrelation of these models is illustrated in Figure 1.

An effectiveness model relates the measures of effectiveness on the functions to be accomplished (the objective) to measures of performance

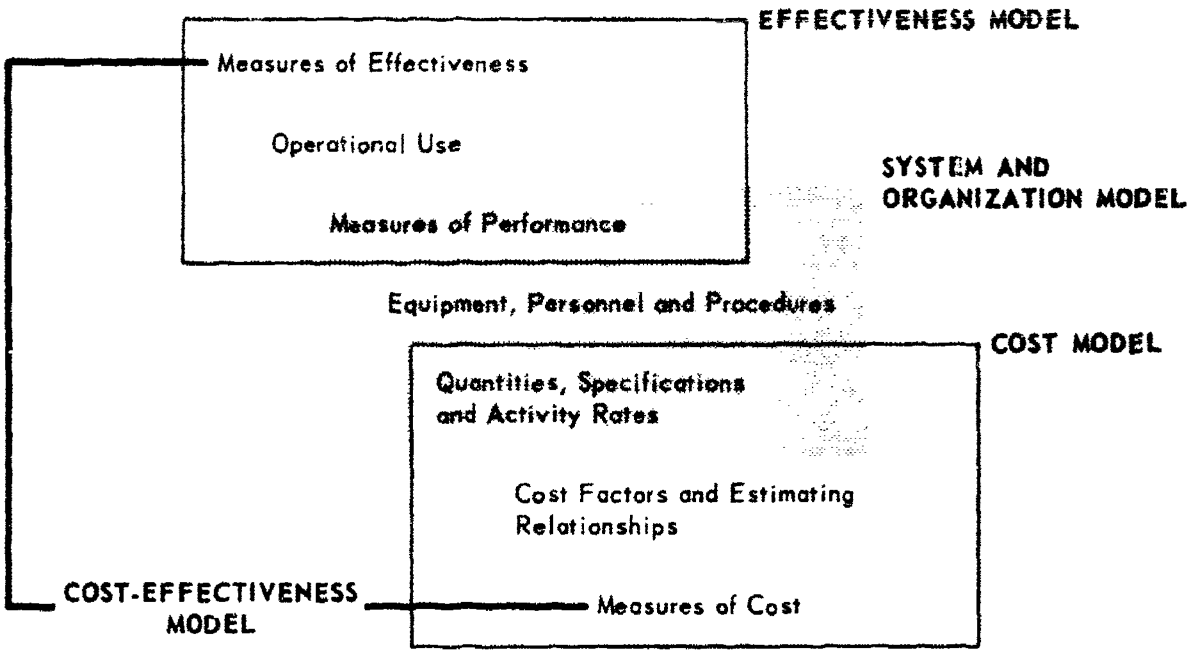

Fig. 1—Principal Categories of Models in Cost-Effectiveness Analysis

in the context of an operational concept.

A system and organization model relates the measure of performance to the physical specifications, quantities, and activity rates of a system and/or organization (equipment, personnel, and procedures) consistent with the operational concept.

A cost model relates the quantities, specifications, and activity rates of the system, and of the organization that operates and/or supports it, to measures of cost through cost factors and estimating relationships.

A criterion or cost-effectiveness model relates cost and effectiveness of each alternative to aid in the selection of the preferred alternative.

The concepts of design and the function of the models as used in the analytical process are illustrated in the following sections (for a comprehensive discussion of modeling, see "Guide for Reviewers of Studies Containing Cost-Effectiveness Analysis.") 2/

DESIGN AND APPLICATION OF MODELS

Within this section, a set of models is described that were designed for the estimation of effectiveness and cost of alternative aircraft systems for the same objective. The models were developed as part of RAC's research in cost-effectiveness methodology.

The Objective

A hypothetical problem is used to illustrate the application of the models. In the example, a military requirement to accomplish a set of tactical missions had been identified, for which one of several different aircraft was to be selected as the principal item of materiel. The

criterion is the lowest peacetime cost for a wartime capability to accomplish the mission requirement on a sustained basis.

An analysis of the objective (operational requirement) revealed the following information:

There were several different mission profiles. All missions required return to the base of operations after completion. A requirement for a specific quantity of missions per day existed in a number of military units located in different operating environments. All of the missions had to be flown on extremely short notice. Demands for sorties were random in time, and there were no priority differences among missions so requested. The different profiles occurred with different relative frequency among military units.

For each of the aircraft, performance, reliability, maintainability, and cost estimates were available, and it had been determined by other means that each aircraft could accomplish the mission tasks.

Support-personnel costs and factors, peacetime activity rates, and other materiel planning factors were available.

Conceptual Design of the Models

The design of the models was based on the following overall concept:

For the measurement of effectiveness, to be expressed as the number of missions per day completed, the wartime operational requirements were to be translated into demands for flying time as a function of aircraft performance (effectiveness model). The demands for flying time were to be translated into numbers of aircraft and personnel as a function of the

aircraft support requirements and policies (systems model). The resource requirements for aircraft and their support to provide a wartime capability were to be translated into peacetime costs (cost model). The effectiveness and systems models, generating physical-resource-requirement data, were to simulate the operations to adequately represent at least some of the more important interdependencies. A flow diagram illustrates the conceptual design of the three models in Figure 2.

The models were to be so designed that all repetitive operations would be performed by a digital computer and all one-time operations by hand. This was an arbitrary allocation dictated by time and manpower constraints. Sequential operations had to be minimized to limit potential bottlenecks in the process of analysis. Computer schedule constraints limited automatic iteration.

Description of Models

Effectiveness Model. The function of this model was to relate effectiveness to performance under simulated operational uses. Its output--ordered demands for flying time--was derived from two principal considerations: the time required to fly each mission profile, and the time distribution of requests for missions.

The relative frequency of mission types at each military unit was calculated manually and its operating environment noted. The time (and fuel) to fly each mission was calculated manually from aircraft performance data for each planned flight profile, for each aircraft, at each environmental condition (altitude and temperature). The flight times

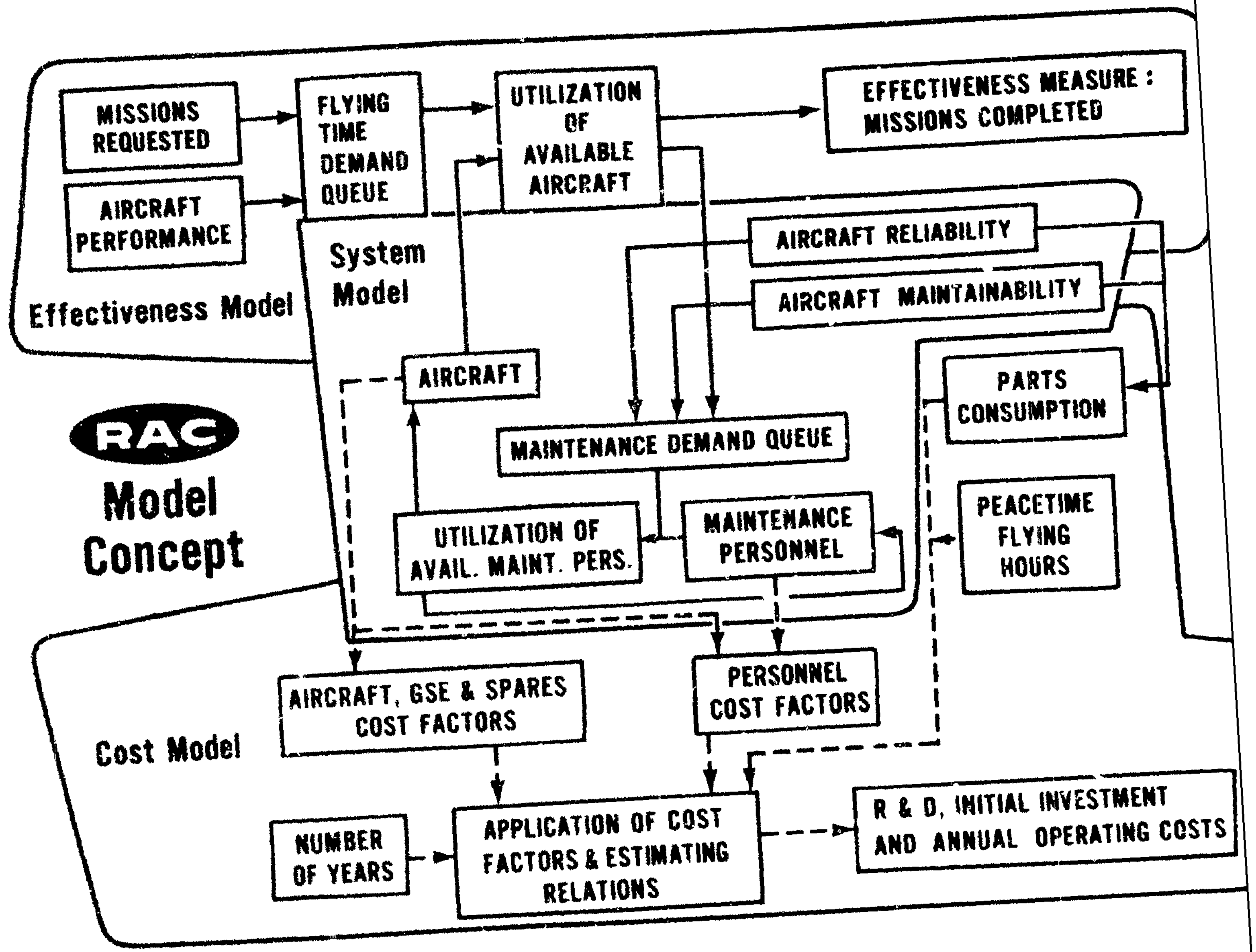

Fig. 2—Flow Diagram of Effectiveness, System, and Cost Models

(and fuel) for each mission/environmental condition/aircraft combination were then matched with the military unit/relative mission frequency/environmental condition combinations to form cumulative frequency distributions for each aircraft/military unit combination.

To simulate the operations, random numbers were selected to draw requests for missions, i.e., flight times, which were ordered in a queue (see Figure 3).

A "dispatcher" in the computer program assigned aircraft from the system model's pool to flight requests under a choice of several policies, e.g., various options on the length of the operations day. At the end of each simulated day, unfulfilled mission requests were canceled.

A "bookkeeping" computer subroutine recorded totals and calculated averages of numbers of missions requested, missions completed, delays, flight time, and fuel consumption for each model run (simulated months of operations).

Systems Model. This model was connected to the effectiveness model via the "dispatcher". The systems model related the flying-time demands and the resulting maintenance requirements to numbers of aircraft and maintenance personnel needed to accomplish the missions as a function of the reliability and maintainability characteristics of the aircraft. Limitations of crew and spare-parts-availability were excluded from this model because they were exogenous constraints, i.e., not directly dependent on the postulated aircraft designs.

Estimates of reliability and maintainability for each aircraft at

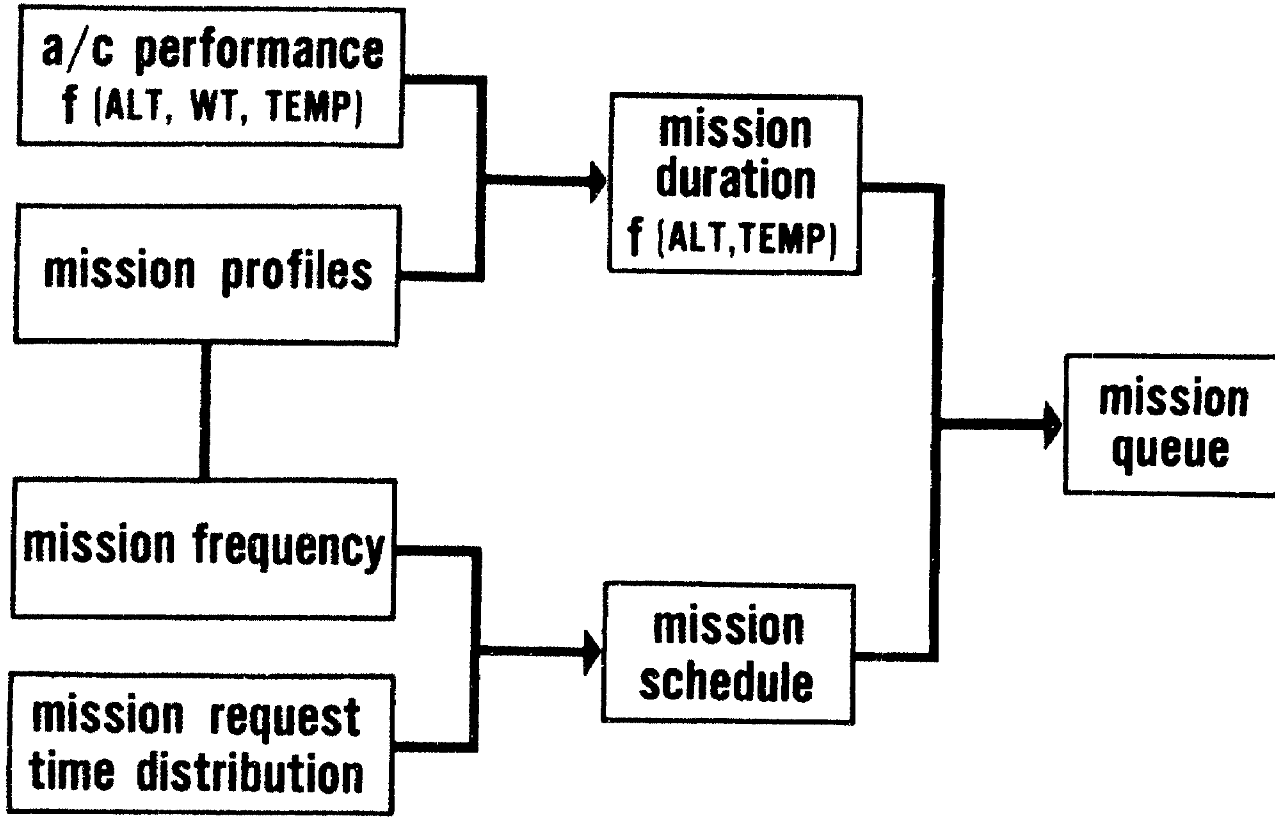

Fig. 3—Effectiveness Model: Aircraft Operational Requirements

each operational condition were analyzed in detail to compute manually the intervals of scheduled maintenance man-hours (accrued on a flying-hour basis but performed after a sortie) and distributions of unscheduled maintenance man-hours per sortie. These times ranged from zero (no repair) to infinity (lost in flight).

For sensitivity analysis, several distributions of unscheduled maintenance were created to reflect assumptions about the impact of higher-echelon repair work as more effort or delay.

The unscheduled maintenance subroutine could also simulate wartime losses of aircraft by adjustment of the "lost-in-flight" percentage to reflect assumptions about effects of vulnerability to enemy action and wartime accidents.

The flow diagram of the systems model is shown in Figure 4. To simplify the model, ground aborts were excluded--it was assumed that if an aircraft were available, it would take off.

Several options for maintenance policies were designed into the model to facilitate sensitivity analysis. For the simulation of continuous operations, both scheduled and unscheduled maintenance were simulated. To test for sensitivity to unscheduled maintenance, the effectiveness model assigned aircraft only during a selected part of the day, scheduled maintenance was assumed to take place during the rest of the day, and only the unscheduled maintenance routine was used. Maintenance personnel could be assigned under several policies reflecting their availability and workload. Aircraft turnaround times were another option.

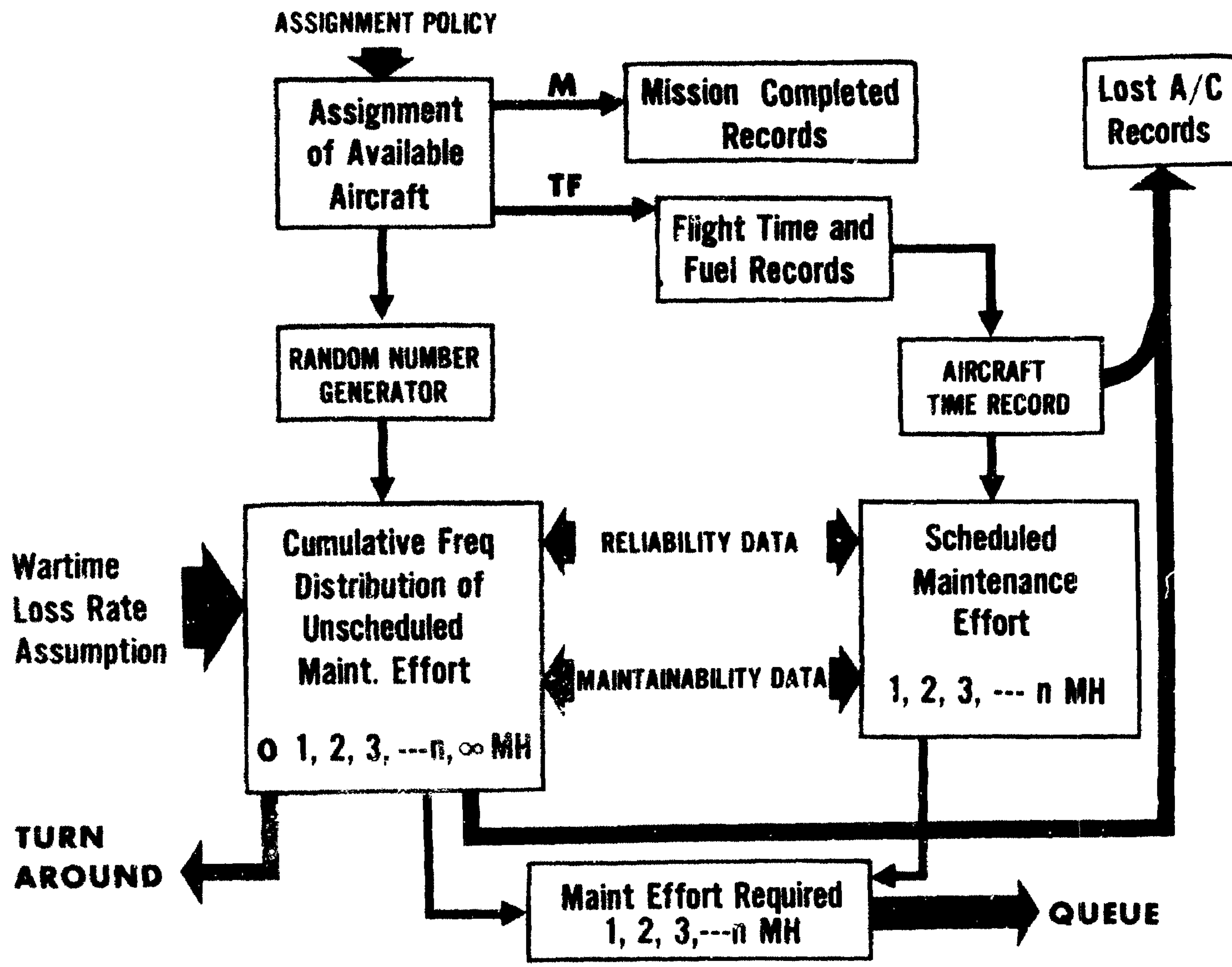

Fig. 4—Systems Model: Aircraft and Maintenance Requirements

After each aircraft's assignment, the records of its simulated cumulative engine time were interrogated to determine if scheduled maintenance were due after the sortie. A random number was used to select the amount of unscheduled maintenance, due after the sortie, from the cumulative distribution. Unscheduled and scheduled maintenance were additive.

If no maintenance were called for, the aircraft was returned to availability status via an optional turnaround time. If maintenance were due, the aircraft entered a queue and awaited assignment of maintenance personnel according to the policy selected, e.g., to assign one available mechanic to any job less than two man-hours, two available mechanics to jobs for two to six man-hours, etc. The computer model calculated the downtime according to the maintenance man-hours required and the maintenance men assigned. Following maintenance, aircraft were returned to availability status. If maintenance were infinite, no mechanics were assigned and the aircraft was entered in the tally as lost (see Figure 5).

The computer programs of the effectiveness and systems models are described in a RAC paper now in preparation: "A Simulation Model for Vehicle Operation with a Set of Stochastic Conditions." 3/

<u>Cost Model</u>. The systems model furnished estimates on the resources (aircraft, personnel, fuel, hours, etc.) required to provide the simulated wartime capability expressed in the measure of effectiveness. The peacetime costs of this capability were computed with the aid of

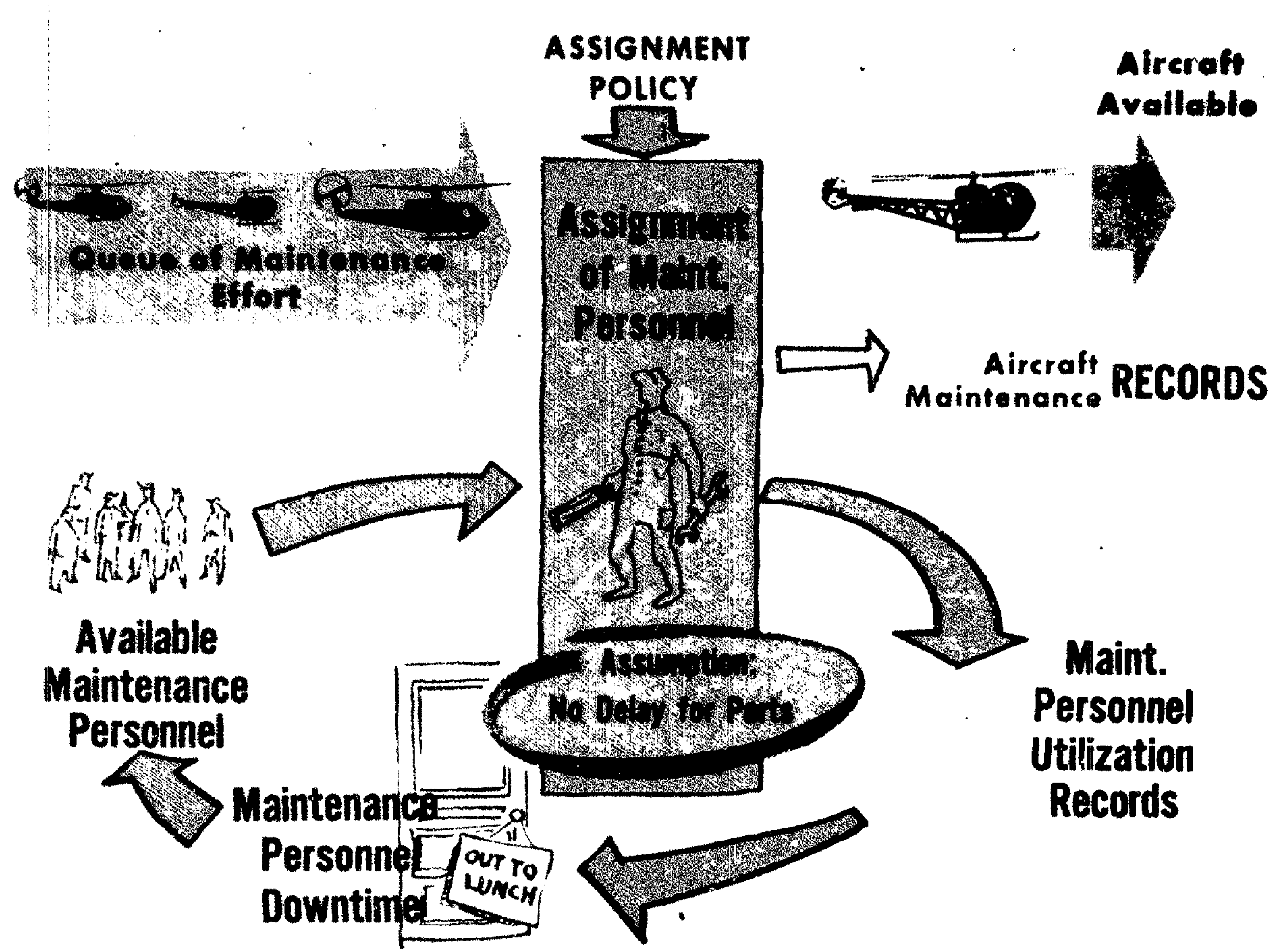

Fig. 5—Systems Model: Aircraft Maintenance and Personnel Requirements

cost models that derived total system costs from the simulated resource requirements by factors and estimating relations.

To conserve time, costing proceeded in parallel with the simulations in the effectiveness and systems models. Research and development costs were estimated separately by hand. Cost sub-models were used to generate separate schedules of costs for aircraft systems and for maintenance personnel so that costs of any combination of these two principal resources could be determined without delay.

Aircraft system acquisition and operational cost factors differed for each aircraft type. They included the complete aircraft itself, ground-support equipment, parts, and fuel consumption. Planning factors for maintenance and replacement of ground-support equipment, initial stocks of spares, peacetime attrition (expressed as aircraft replaced per 100,000 flying hours), maintenance float, and training aircraft were common to all designs.

The cost factors were entered into the computer sub-models, which calculated the initial investment and annual operating costs for the given numbers of aircraft, years of operation, annual flying hours, and attrition factors, and then added to these the costs of research and development. The sub-models for initial investment and annual operating costs are illustrated in Figures 6 and 7, respectively.

Preparation of the input data was a manual process often requiring considerable analysis and use of estimating relations (the types of cost model input data are listed in Figure 8).

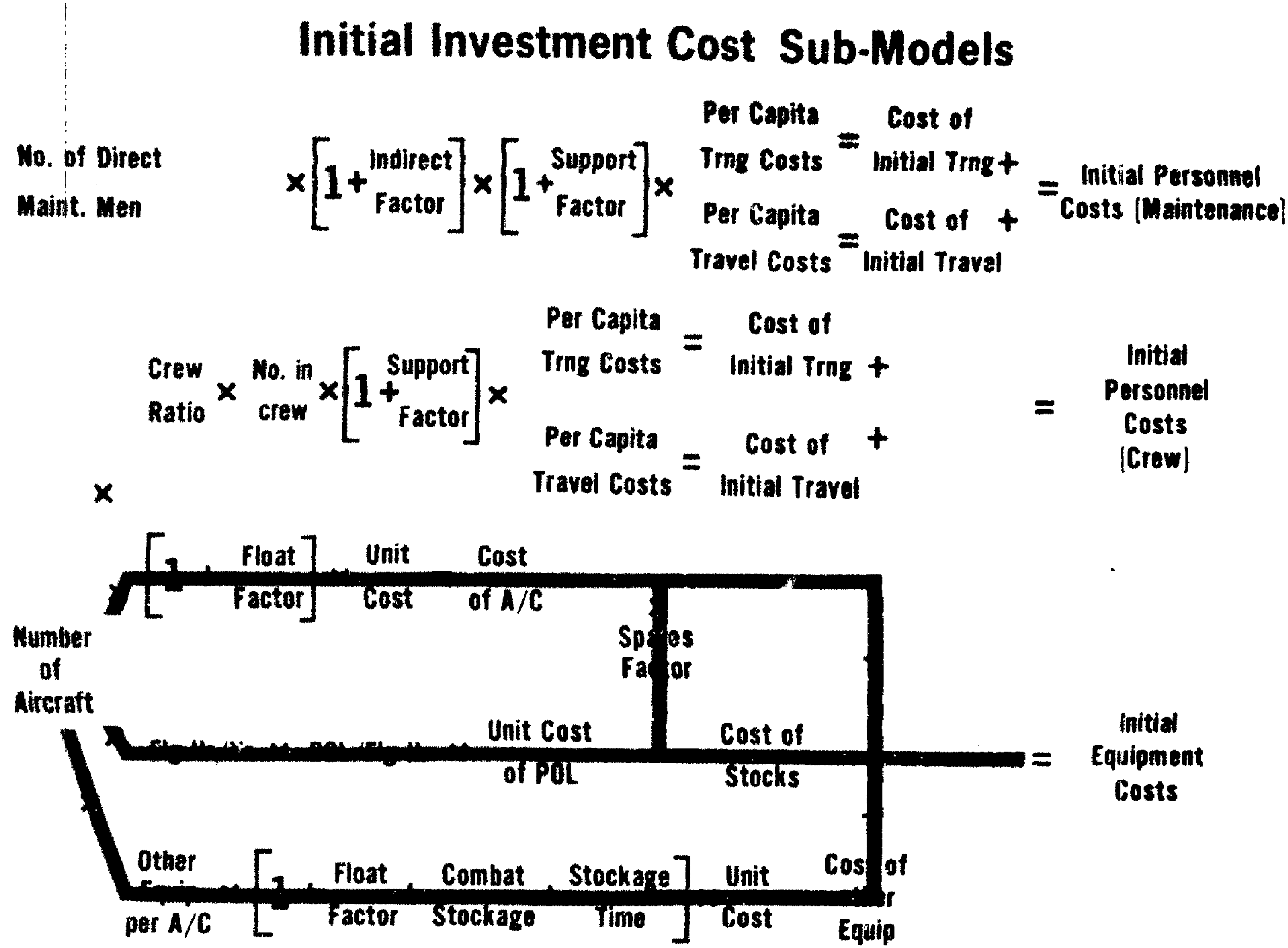

Fig. 6—Cost Model Subroutine for Calculating Initial Investment Costs

TYPES OF INPUTS TO COST ANALYSIS MODEL

Materiel

- Research and development costs
- Quantities of equipment
- Unit costs
- Maintenance float and stockage factors
- Flying hour programs
- POL consumption and costs
- Annual replacement of equipment
- Maintenance costs per flying hour
- Other maintenance costs

Personnel

- Maintenance personnel
- Crew ratio
- Crew mix by personnel type
- Support factor
- Training costs
- Pay and allowances
- Turnover rates
- Travel costs
- Other personnel related cost factors
- Direct/Indirect factor

Fig. 8—Cost Model Input Data

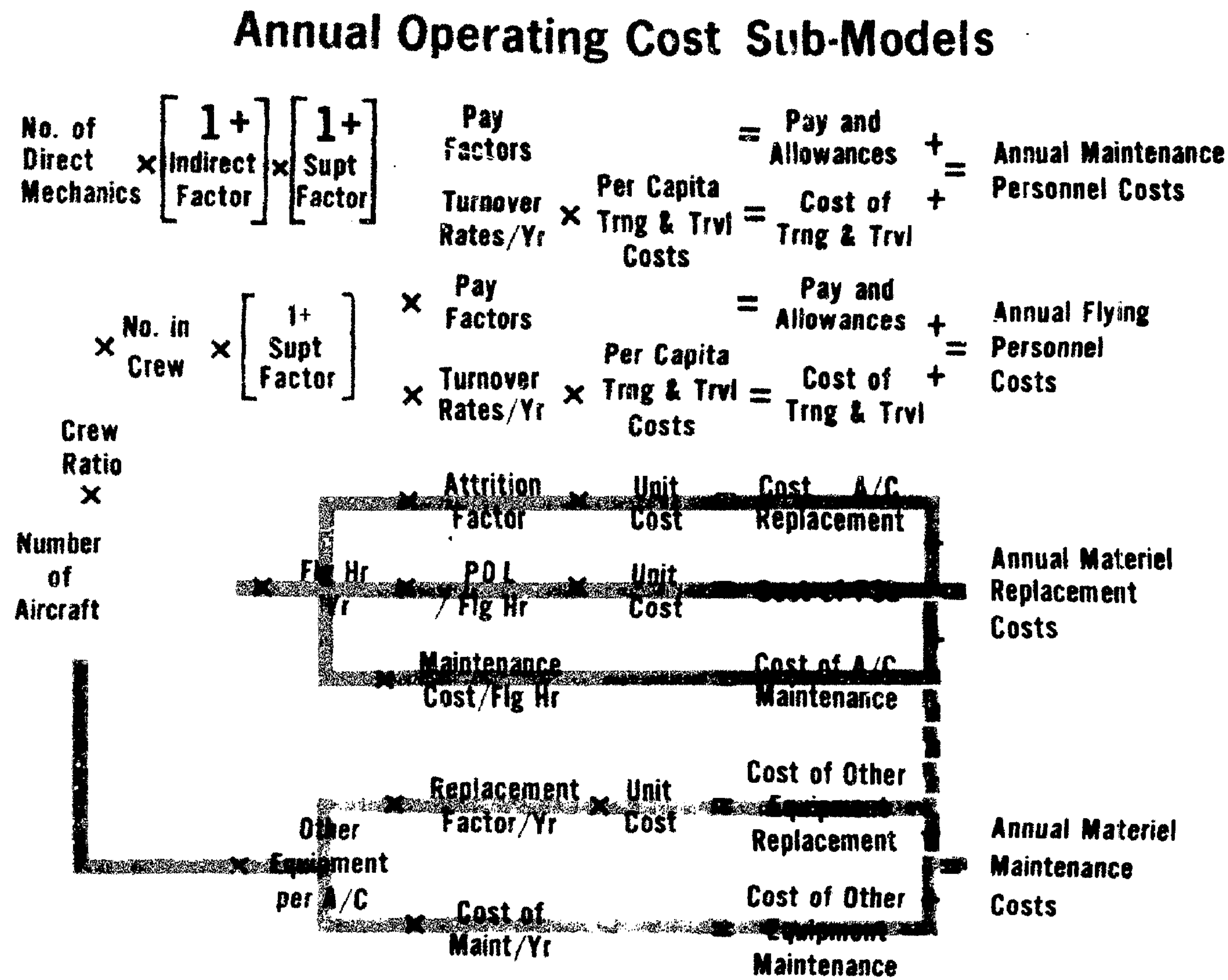

Fig. 7—Cost Model Subroutine for Calculating Annual Operating Costs

For the estimation of the spares-cost per flying hours, the scheduled and unscheduled maintenance data prepared for the system model were used.

A detailed description of the cost model computer program will be published in a future RAC paper, now in preparation: "An Individual System/Organization Cost Model." 4/

Sensitivity Analysis. In each of the models discussed above, calculations were repeated with small changes in input values, and with different simulation rules (options or policies) to determine the sensitivity of the results to such changes (see Figure 9). In this manner, assumptions were identified which must be explicitly included in the information presented for the selection of the preferred alternative.

Cost-Effectiveness Model. To select the preferred alternative, a criterion is applied relating cost and effectiveness in some specified manner. As mentioned earlier, the preferred alternative was to be selected on the basis of the lowest peacetime cost for a specified level of effectiveness, i.e., wartime capability.

The cost-effectiveness model is not a computer program; rather, it is a type of decision model. Without going into a lengthy discussion of the theoretical aspects of resource allocation decisions, a series of simplified illustrations will be used to describe the cost-effectiveness model - the raison d'être of the computer models discussed above.

Simulations by the effectiveness and system models showed that the same level of effectiveness, i.e., missions completed per day, could be obtained for each of the alternatives with several different combinations

ANALYSIS OF SENSITIVITY TO

- **Mission Profiles** (OPERATIONAL REQUIREMENT)
- **Time Distribution of Request**
- **Frequency Distribution of Mission Profiles**
- **Assignment Policies**
- **Activity Rates**
- **Aircraft Costs**
- **Aircraft Maintenance**
- **Aircraft Performance**

Fig. 9—Sensitivity Parameters

of maintenance personnel and aircraft systems. This limited substitutability is illustrated, albeit exaggerated, in Figure 10 for Alternative 2. Each point on the curve represents a combination of aircraft systems and maintenance personnel which will yield the same effectiveness. Figure 11 shows the equal-effectiveness curves of all three alternatives: each point on each of the three curves represents the same number of missions completed per day.

The cost models furnished schedules of cost for aircraft systems and for maintenance personnel, respectively. Different combinations of maintenance personnel and aircraft systems can be obtained for a given budget. Figure 12 shows these combinations for several budget levels for one of the alternatives. Each point on a given line represents a combination of maintenance men and aircraft systems available for the budget expressed by that line. The slope of the line is determined by the relative costs of these two factors.

Figure 13 illustrates the combinations of maintenance personnel and aircraft systems for each of the alternatives at two budget levels. Because of differences in costs among the three alternative aircraft systems, the relative costs of maintenance personnel and aircraft systems, i.e., the slopes of the budget lines, differ for each alternative.

For each alternative, many different combinations of factors can be obtained for the same cost, and many different combinations will yield the same level of effectiveness, but only one combination is the most efficient for each alternative. This concept is illustrated in Figure 14,

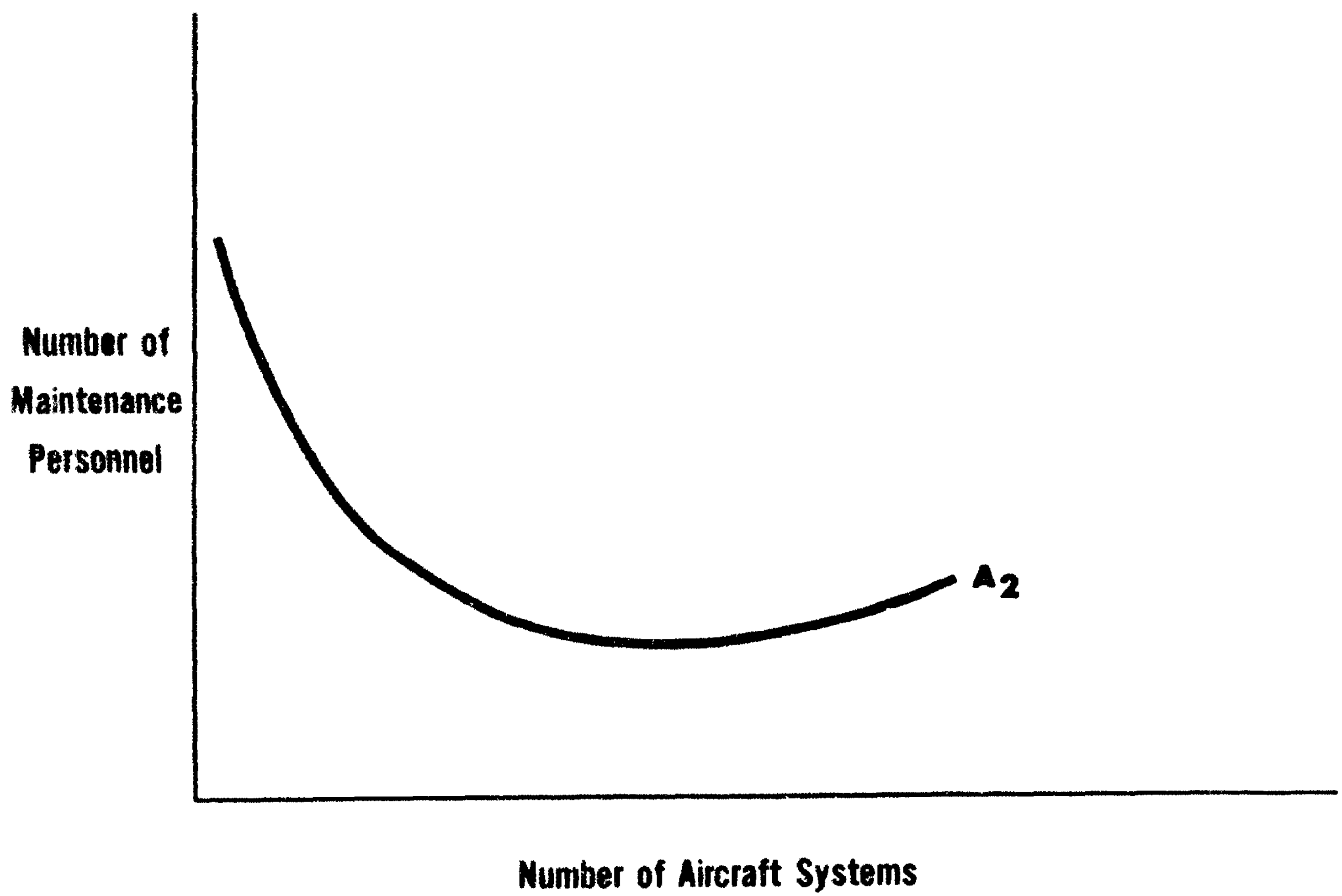

Fig. 10—Equal-Effectiveness Curve of One Alternative

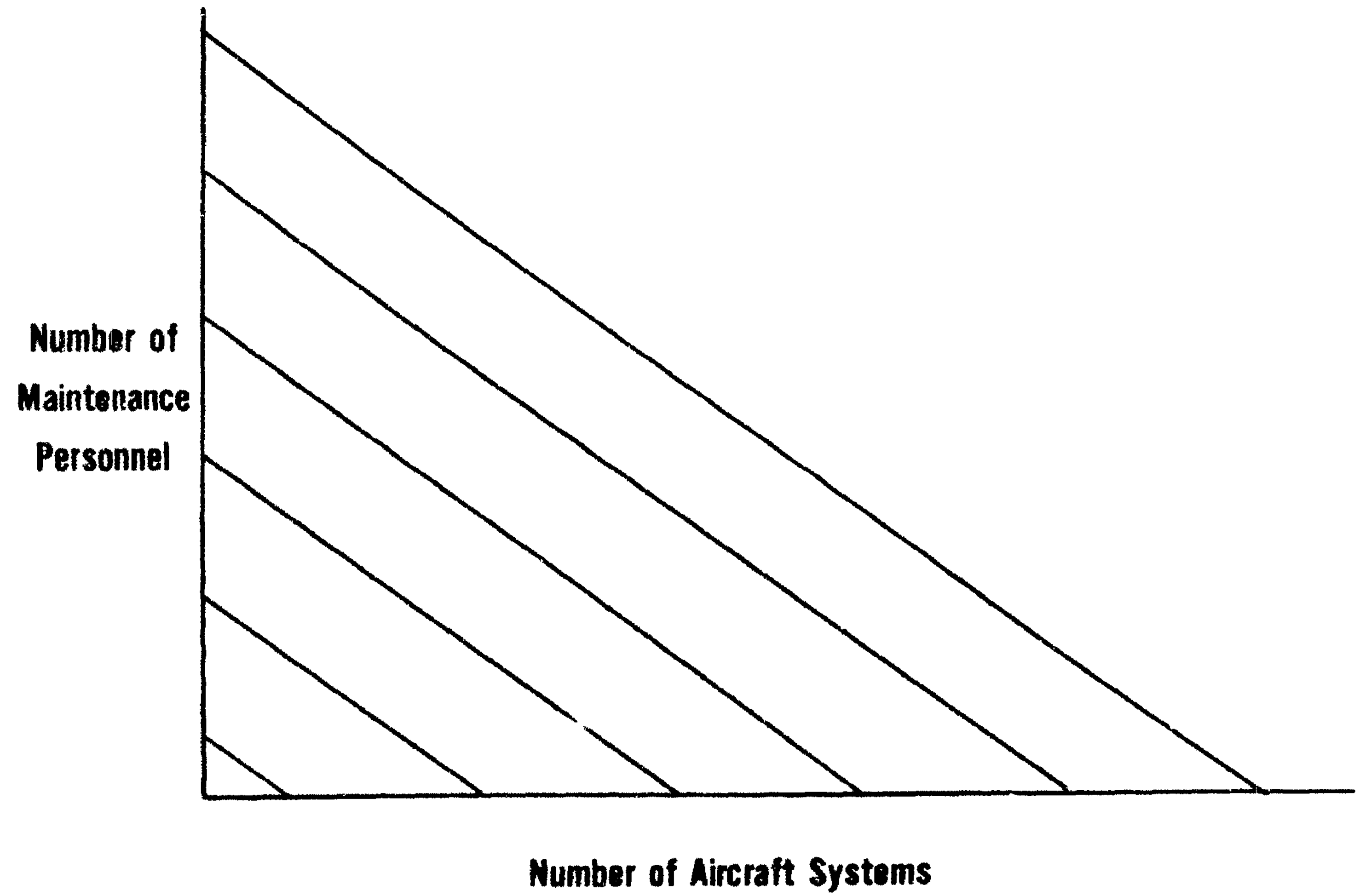

Fig. 12—Equal-Cost Lines (Budget Levels) for One Alternative

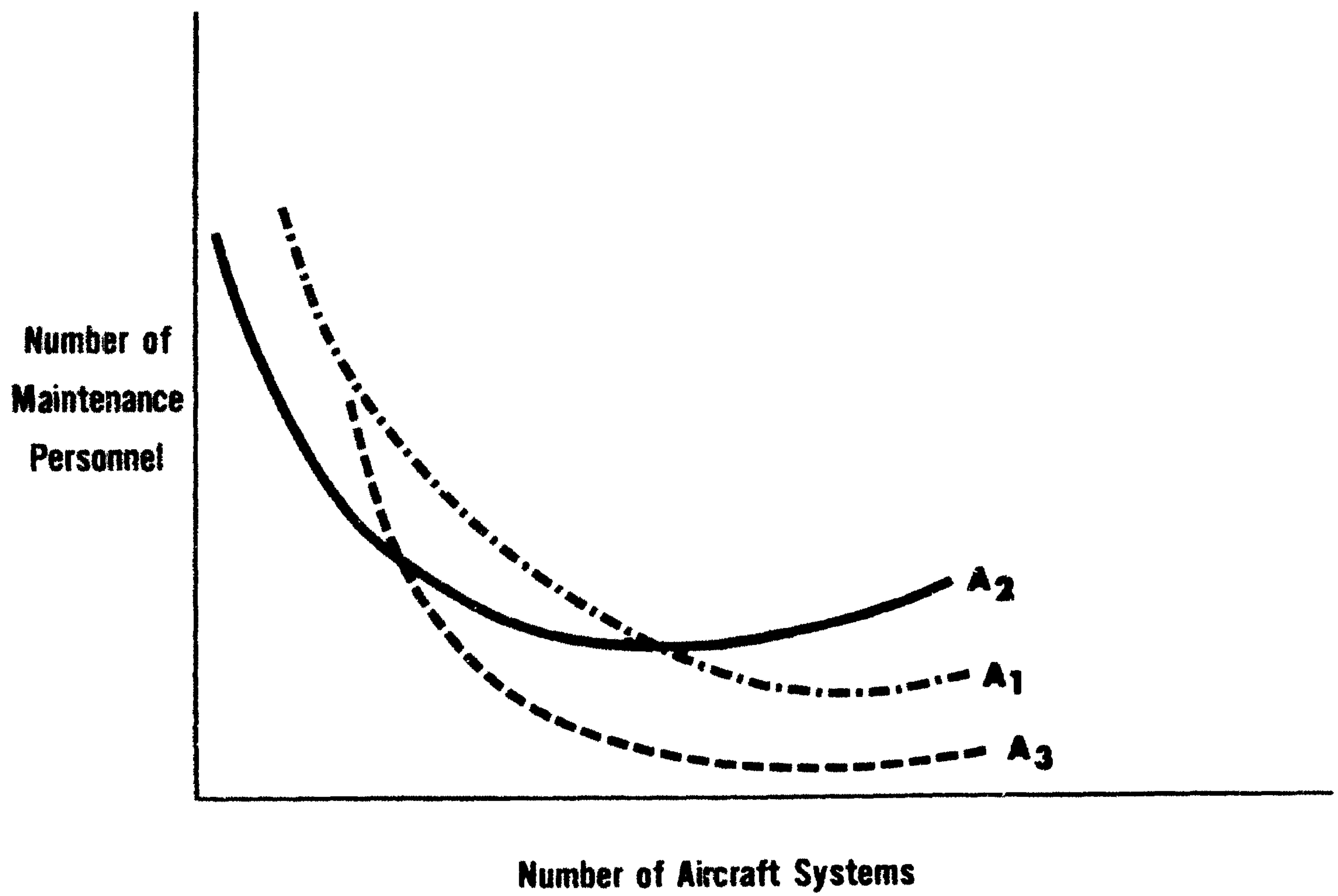

Fig. 11—Equal-Effectiveness Curves of Three Alternatives

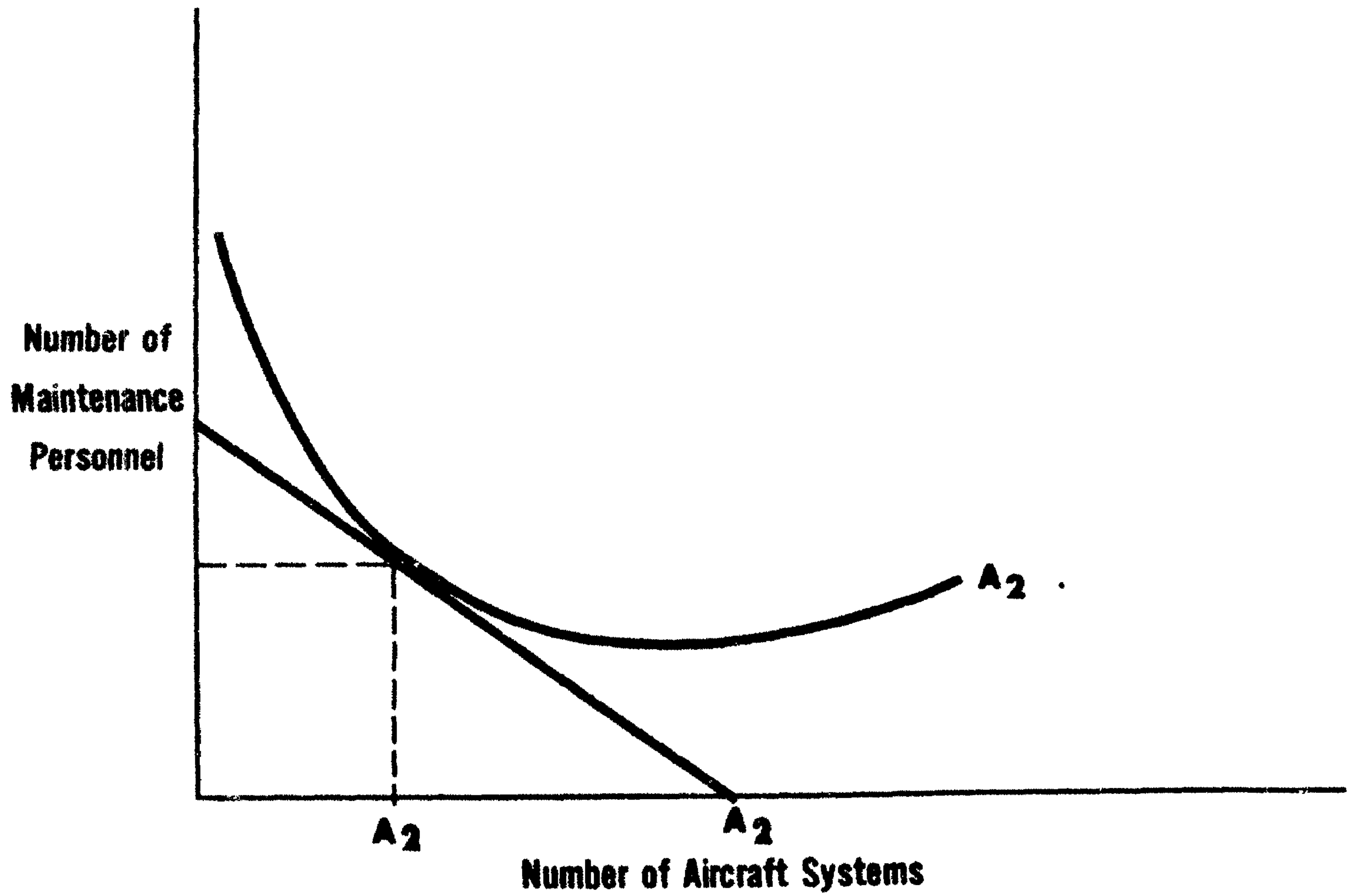

Fig. 14—Optimization of One Alternative

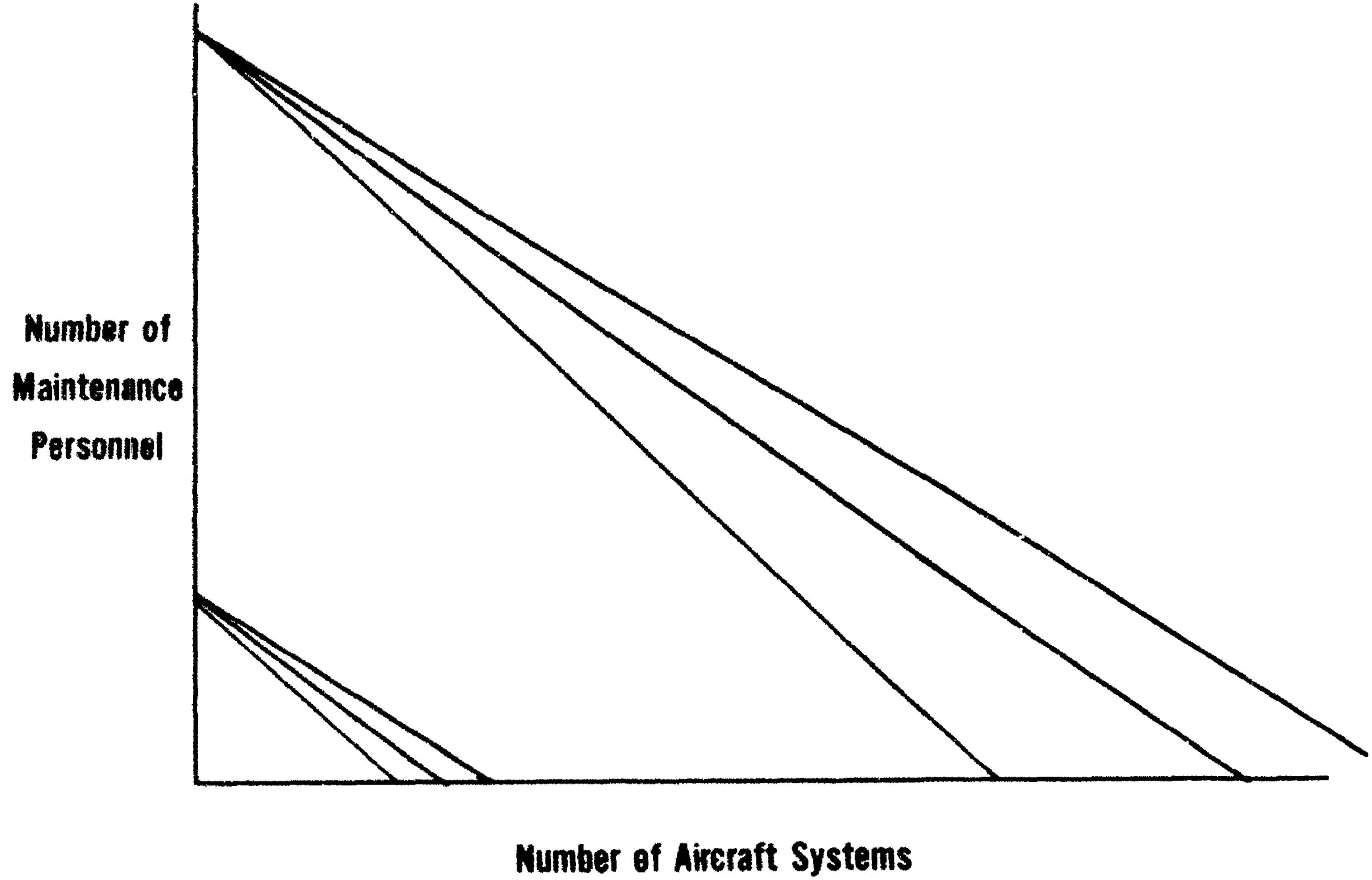

Fig. 13—Equal-Cost Lines (Budget Levels) for Three Alternatives

which shows the equal-effectiveness curve of Alternative 2 (as shown in Figure 10) and the equal-cost line for Alternative 2 which is tangent to that curve. The combination of maintenance personnel and aircraft systems defined by this point of tangency of the equal-effectiveness curve and the equal-cost line is the most efficient for Alternative 2. Any other combination would cost more or accomplish less.

Figure 15 is the cost-effectiveness model. It shows all three alternatives compared at the same level of effectiveness. Alternative 1 will accomplish the objective at the highest cost; Alternatives 2 and 3, respectively, at less cost than Alternative 1. Alternatives 2 and 3 have the same cost and effectiveness and differ only in the ratio of maintenance personnel to aircraft systems. Given the original criterion, no preference between Alternatives 2 and 3 can be stated; other criteria, e.g., implicit different relative scarcities between the principal appropriation categories affected [Military Pay, Army (MPA) vs Procurement of Equipment and Missiles, Army (PEMA), and Operation and Maintenance, Army (OMA)] or the many aspects of real aircraft, listed in Figure 16, which were not modeled, would have to be considered to select a preferred alternative.

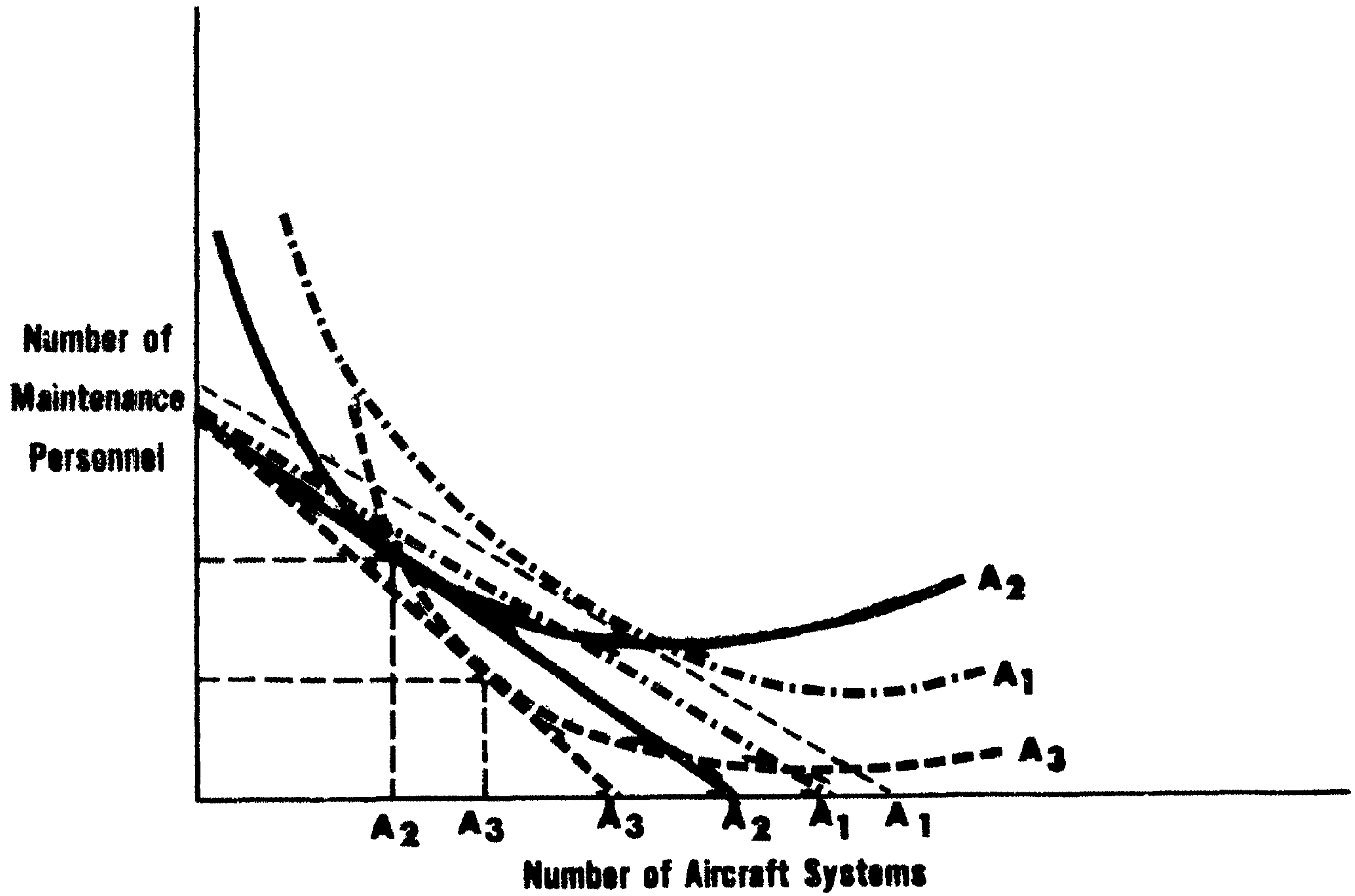

Fig. 15—Cost-Effectiveness Model

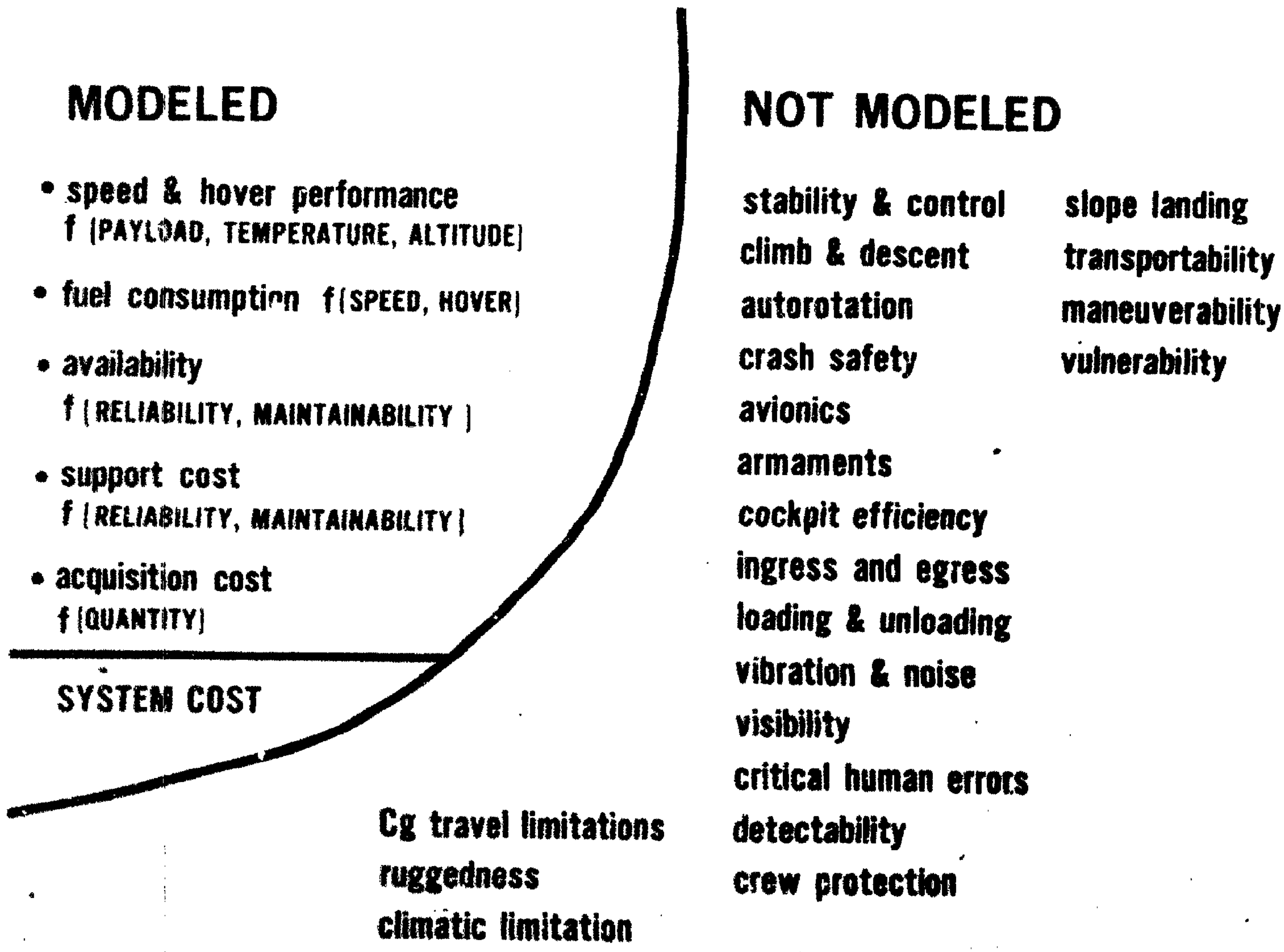

Fig. 16—Included and Excluded Characteristics

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